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A Pulsed Ruby Laser System for Use in Dynamic Photo Mechanics

Army Missile Res. Dev. & Engineering Lab, Redstone Arsenal, Ala.

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A PULSED RUBY LASER SYSTEM FOR USE IN DYNAMIC PHOTO MECHANICS

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September 1975

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This report was written to demonstrate how a pulsed ruby laser provides an excellent light source for use in various areas of holography and photoelasticity. The present investigation was undertaken in order to develop a ruby laser system suitable for photomechanics research.

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1. Introduction

The ruby laser is one of many types of lasers whose popularity has grown steadily since its initial development by H. T. Maimam in 1960. Ruby lasers are called solid-state devices because a solid ruby rod doped with a small amount of chromium is used as the active material. The ruby material is optically excited by radiation from flash lamps in a way such that random pulses of high intensity and temporally coherent (i.e., monochromatic) light energy are emitted. A typical output from such random lasing is shown in Figure 1. Each sharp spike in the trace represents a random pulse during a single firing of the flash lamp.

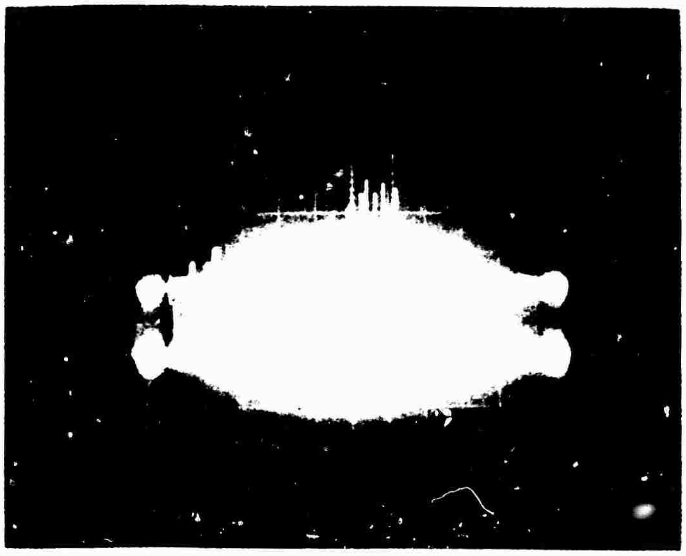

Figure 1. Random output from a ruby laser. (Light intensity is shown on the vertical axis. Bottom trace is the same output as the top trace with a faster sweep speed.)

During the initial development, ruby lasers were restricted in application due to the inherent random output. Observe in Figure 1 that random lasing occurs over a time period of approximately 1 msec. This time duration is too long for any type of high speed events. A method for removing these undesirable irregularities and simultaneously increasing the peak output light intensity was first proposed by Hellwarth [1]. This popular method of control is generally referred to as "Q-spoiling" or "Q-switching". The Q-switching technique makes possible an output of a single giant pulse of highly intense and coherent light energy. This giant pulse is usually confined to a very short time duration (50×10^{-9} sec). A typical output from a Q-switched ruby laser is shown in Figure 2.

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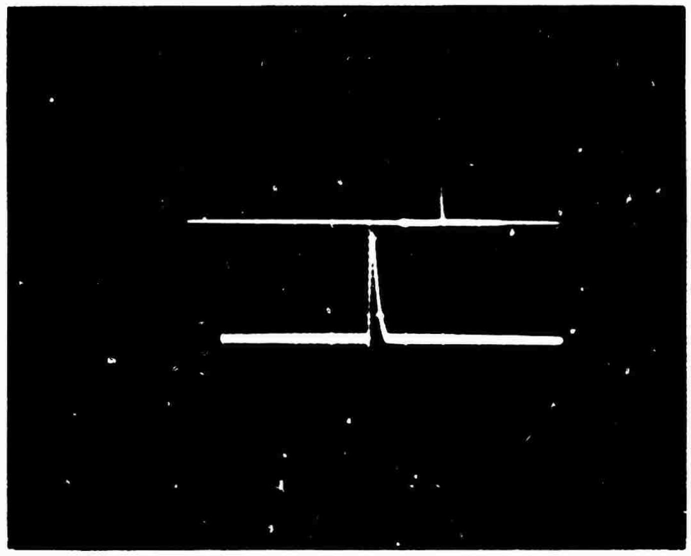


Figure 2. Typical light output from a Q-switched ruby laser.

The development of the Q-switching technique aroused much interest in the ruby laser. By employing this method, a highly intense, monochromatic light source with an extremely short pulse duration was made available. Thus, the Q-switched laser was recognized to be an especially well suited tool for studying high speed events. In the last few years the Q-switched ruby laser has been successfully applied in the area of photomechanics for studying various dynamic phenomena [2, 3, 4, 5, 6]. Certain features of the pulsed ruby laser are responsible for its adoption in areas of photomechanics. These features are in the following paragraphs.

a. High Output Power

By utilizing Q-switching techniques to obtain a single giant pulse, the peak output power may be increased by at least two orders of magnitude over that obtainable by random lasing. Within two years from the first experiments, giant pulses were produced exceeding the power level of 100 mw. Also meaningful is the total energy radiated in one flash. This depends on the excitation and size of the ruby; values between 0.1 and 1.5 J may be typical for ruby rods approximately 1 cm in diameter and 4 cm in length. Much depends, of course, on the excitation, quality of the ruby, and the reflectors. Larger lasers which deliver hundreds of joules in a single flash are commerically available and the records of the energy output per flash are continually increasing.

b. Short Pulse Duration

The Q-switching operation allows for an output of a single giant pulse as well as a large number of controlled pulses in succession. Q-switched pulse rates greater than 200,000 pulses/sec are obtainable. An individual pulse duration of approximately 50 nsec is easily obtained and is sufficient to effectively "stop" photographically a deforming body in its instantaneous position throughout its exposure to the pulse of light.

c. Temporal and Spatial Coherence

The property of temporal coherence (i.e., light energy of a single wavelength is inherent in the production of light by the phenomenon of lasing. All lasers exhibit the basic property of producing a highly monochromatic light emission. Such a property is of utmost importance if the light source is to be used in holographic interferometry and photoelasticity studies. The ruby laser is highly monochromatic and operates at a wavelength of 6943 Å.

A usable light source (for holography in particular) must also emit light energy having the property of spatial coherence (i.e., the output beam must be spatially in phase). This property allows the laser to operate in a single mode. With a suitable choice of the laser cavity and output mirrors, pulsed ruby lasers can be made to operate in the transverse electromagnetic $(TEM)_{00}$ mode which is necessary for holography. In simple terms, the TEM_{00} mode is present when the expanded light beam has a uniform circular Gaussian intensity pattern. The necessary components and arrangement for controlling the operational modes of the laser are discussed in detail in the succeeding paragraphs of this report.

d. Degree of Polarization

Plane polarized light is produced when the electric field of the light energy is made to pulsate in a single plane. Since a plane polarized beam of light is frequently required in photomechanics, lasers are often built so as to emit plane polarized light. The polarization of the ruby laser output depends on the orientation of the optic axis with respect to the cylindrical axis of the rod. According to the measurements of Nelson and Collins [7], the output is complete unpolarized when these axes are parallel. A ruby rod with an optic axis forming a 60° or 90° angle with the cylindrical axis gives a 100% linearly polarized output with the electric vector perpendicular to the plane containing the optic axis. A ruby laser, then, may be constructed to provide a source of highly polarized light energy.

e. Operational Wavelength

The ruby laser, when operating without mode control (random lasing), exhibits some variation in output wavelength with temperature changes. An empirical relation between wavelength and temperature is given by Lengyel [8]. A 10°C increase in temperature increases the wavelength by almost 0.7Å. By modulating the laser so that it operates in a single mode, the output wavelength may be held constant to within a small fraction of an angstrom. At room temperature the ruby laser operates at approximately 6943 Å. This is in the red portion of the spectrum which is desirable for photomechanics applications.

2. Construction of the Laser

a. General Description

The working element of a ruby laser is a cylindrical rod of pink ruby crystal in which a small amount (approximately 0.05%) of aluminum atoms have been replaced with chromium atoms. The ruby rod is excited or "pumped" by radiation from a flash lamp. When the flash lamp is triggered, it emits a green and blue flash of short time duration. Normally, the chromium atoms are in a nonexcited or ground energy state. When the photons from the flash lamp bombard the ruby rod, orbiting chromium electrons are pumped into a higher energy state (Figure 3). The electrons have absorbed pumping energy and have become highly excited.

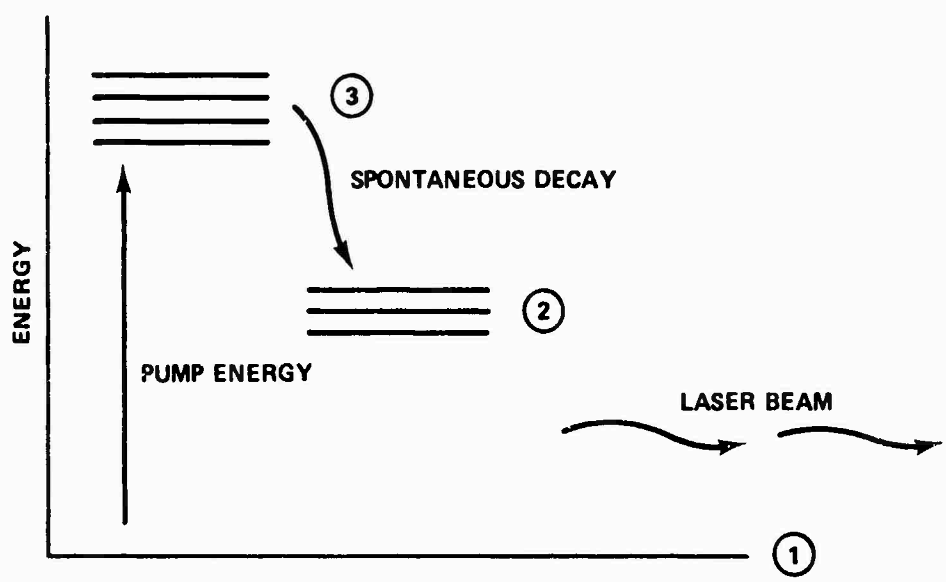


Figure 3. Energy level diagram of chromium ions in ruby.

This state is labeled energy level 3 in the figure and consists of a band of energy levels lying close together. The energy from the flash lamp consists of several different frequencies of radiation, but only certain ones can contribute to the pumping action.

Most of the absorbed energy is transfered by fast, nonradiating transistions into energy level 2. The energy difference is given up to the crystal lattice as heat. The energy level 2 is metastable (long-life) state. It is possible for atoms to accumulate there until level 2 becomes more highly populated than the ground state, level 1. Recall that this is the condition known as population inversion.

If the atoms in energy level 2 are allowed to spontaneously return to ground level in a random fashion, ordinary (incoherent) red light will be emitted. This is the normal process of fluorescene where energy is absorbed and then emitted as light. To utilize the population inversion to produce laser energy, a resonant cavity is needed.

The most basic resonant cavity consists of two reflective surfaces, one placed at each end of the ruby rod (Figure 4). The photons emitted from the ends of the rod will be reflected back into the rod. One mirror is slightly transparent so that the beam can pass through when it has reached a high enough intensity. (The ends of the ruby rod itself may be polished and treated so that they act as the mirrors.) With this resonant cavity, a beam will originate when an excited atom emits a photon parallel to the axis of the ruby rod. (Emissions in other directions do not contribute to the process.) This and other photons reflect successively between the mirrors at each end of the rod. During each traverse, the photons trigger other excited atoms, and they too emit photons. This continues until all the excited chromium atoms have given up their energy in a chain reaction. When the beam has attained a high enough energy, a pulse of laser light is transmitted through the partially reflecting mirror. Note that the resonant cavity makes possible the necessary "feedback" process to produce the laser energy.

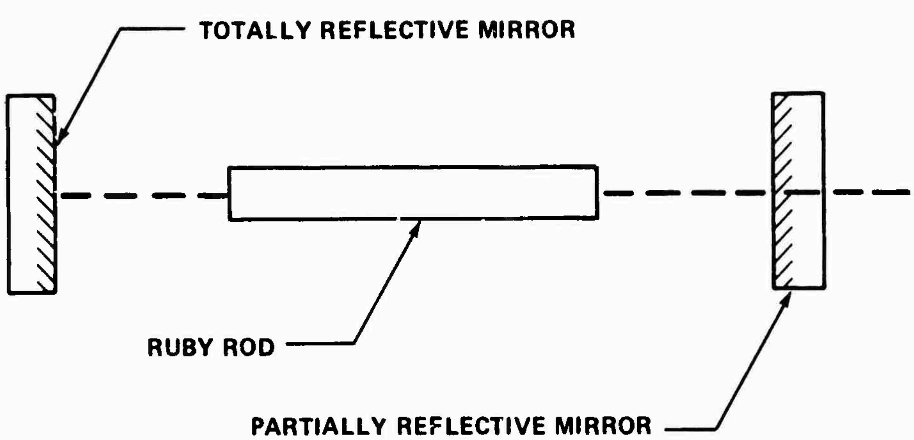


Figure 4. Resonant cavity

As indicated, a high intensity flash lamp is used to provide the pumping energy necessary to raise the chromium atoms to an excited state. In the ruby material, the flash energy absorbed is of a frequency equivalent to the color of green. Up to a certain critical flash intensity, only normal fluorescence occurs. If, however, the intensity of the flash lamp is above this critical level, lasing action takes place. This happens because the atoms will collect in energy level 2 (Figure 3) sufficiently fast to allow a population inversion to occur only when the pumping energy is high enough. The first few photons emitted along the ruby axis then begin to traverse in the resonant cavity, thus allowing stimulated emission to take place.

From the preceding discussion, it is apparent that as much of the flash lamp energy as possible should impinge on the ruby rod. In the first ruby lasers, the flash lamp was usually in the shape of a coil which spiraled around the ruby rod (Figure 5). Much of the energy from this type of flash lamp is radiated outward and not absorbed by the ruby rod. More efficient configurations are shown in Figure 6 and Figure 7. In Figure 6, the rod and flash lamp are housed in a reflecting tube and placed at the focal points of the elliptically shaped inner surface. The inner walls are polished and act as a mirror so that all the light energy from the flash lamp is reflected into the ruby rod. In Figure 7, the ruby rod and two flash lamps are housed in a double elliptical cavity. The rod is placed at the common focal point of both ellipses. The reflection diagram for each configuration is shown in Figure 6 and 7. These are only two of a large variety of flash configurations which have been used in an attempt to attain as much efficiency in pumping as possible.

b. Cavity Geometry and Mode Control

The most restrictive requirement of the ruby laser for applications in photomechanics is the mode control necessary for holographic interferometry. To be of use in holography, the ruby laser must be operated with a high degree of transverse and axial mode control. These properties are difficult to control and can be relaxed considerably for applications in photoelasticity and Moire´ fringe analysis. Proper mode control, however, ensures a laser output of high spatial and temporal coherence.

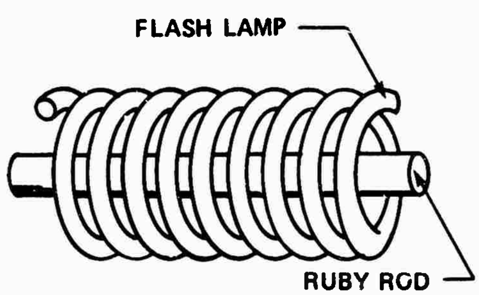


Figure 5. Early flash lamp design.

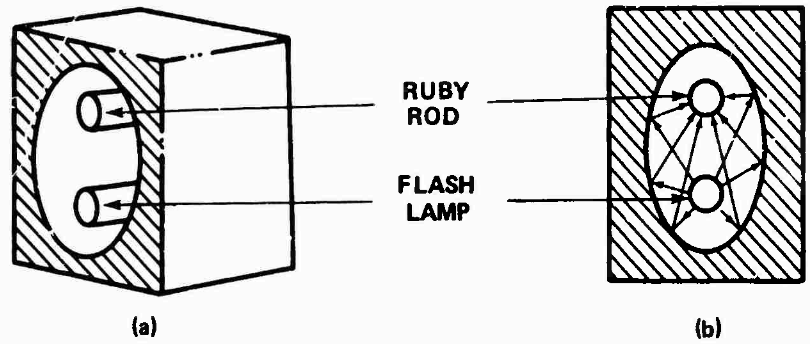


Figure 6. Elliptical flash configuration.

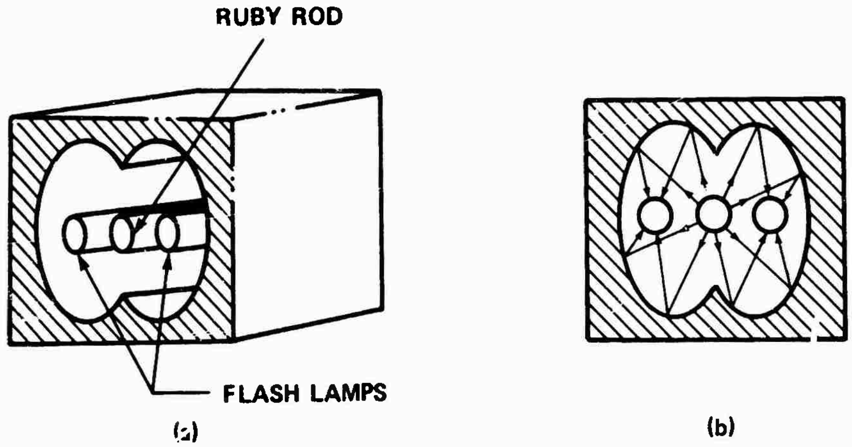


Figure 7. Double elliptical flash configuration.

The modes of operation refer to the modes of oscillation of the electromagnetic field of the light energy. A uniform plane wave in which both the electric and magnetic vector are perpendicular to the direction of propagation is of the transverse TEM mode type. By proper transverse mode control, the ruby laser may be made to operate in the fundamental TEM_{00} mode. When operating in this mode, the expanded output beam has a uniform circular Gaussian intensity distribution which is unbroken by any bars or bands. Examples of intensity patterns for various operational modes, as given by Levine [9], are shown in Figure 8.

Transverse mode control is best obtained by properly selecting a high quality ruby rod (i.e., a resonating cavity configuration that discriminates against all transverse modes other than the fundamental TEM_{00} mode) and by inserting aperatures within the resonant cavity itself.

To obtain a small loss of TEM_{00} and a large loss of higher transverse modes (TEM_{01}, TEM_{11}), it is necessary to place an aperature in the resonant cavity. This was done by placing an adjustable iris diaphragm

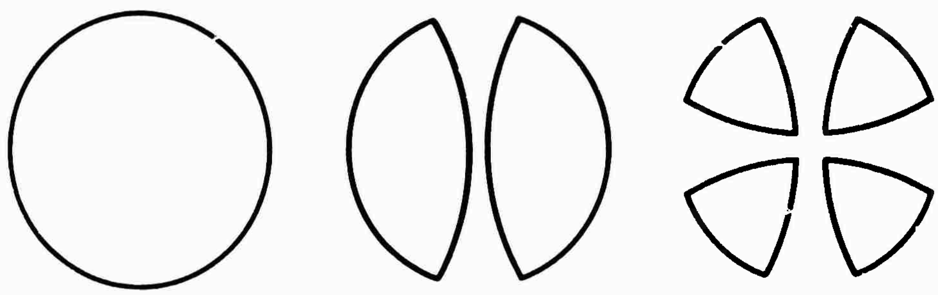


Figure 8. Mode configuration.

near the plane output mirror of the system (approximately 4 in. away). The diffraction loss of a transverse energy mode in the resonator is a function of the radius of the mirrors, the mirror spacing, and the size and shape of the mirrors. Diffraction losses, per transit through the resonator, are often given as a function of the Fresnel number which is expressed as

$$N = \frac{\bar{a}^2}{L\lambda}$$

where

$\bar{a}$ = the effective mirror radius (which depends on the size of the diagram hole)
L = the separation distance of the mirrors
λ = the light wavelength.

If the mirror radius is 5.0×10^{-4}m and $L = 0.5$m (the approximate dimensions actually used in the resonator), $N = 0.72$ and according to reference [9], a TEM_{00} mode power loss of approximately 1% occurs while the power loss of the next higher mode TEM_{10} is approximately one order of magnitude larger. By opening the iris diaphragm further (and increasing the Fresnel number value), the TEM_{00} loss decreases but the TEM_{01} loss decreases simultaneously. Diaphragm diameters from 1 to 2 mm were used in all holography experiments described in this report. As discussed previously, longitudinal or axial mode control is also a necessary requirement. In simple terms, axial modes may be described as follows. As light waves reflect back and forth in the resonator, they will meet in reinforcement only if the optical distance traveled between mirrors is an integral multiple of the half-wavelength of the light. Light waves that are directed along the laser axis and are of a frequency such that reinforcement does occur are called the axial modes of the laser. They are analogous to the free oscillating modes of a damped harmonic oscillator.

Since the lasing action occurs only above a critical theshold condition, laser oscillations will occur only for a finite number of axial mode frequencies which lie in this restricted range (Figure 9).

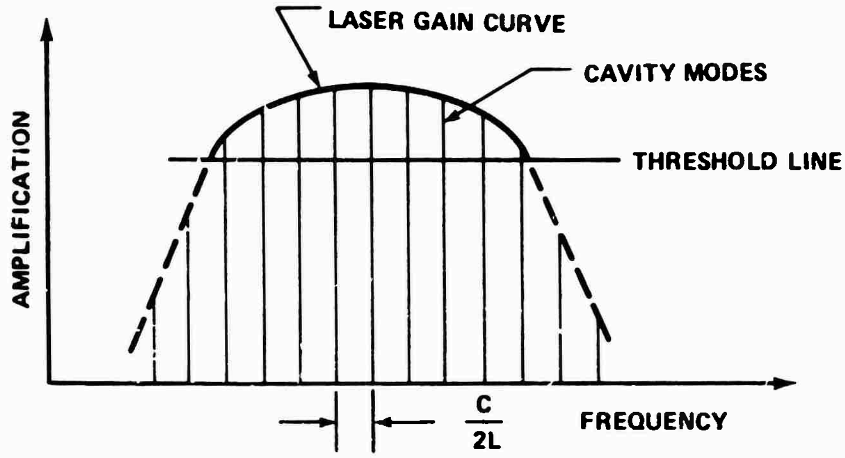


Figure 9. Laser gain as a function of frequency.

The possible axial modes have a spacing of C/2L where L is the distance between mirrors and C is the speed of light. If L = 0.5 m, the frequency spacing will be 3×10^8 Hz. The range of operational wavelength (often called bandwidth) of a ruby laser with no axial mode control may approach 1Å. This bandwidth corresponds to a frequency spread of approximately 6×10^{10} Hz; thus, there are approximately 200 possible axial modes in which the laser can operate. Obviously, some method of limiting the number of axial modes and simultaneously reducing the operational bandwidth is needed. It is apparent that by reducing the resonant cavity spacing (i.e., by decreasing the value of L) the frequency spacing will be increased so that only a few or just one axial mode will exist within the laser operating curve. According to Levine [9], however, shorter laser systems mean reduced output power. Also, the need for space to insert apertures and devices for Q-switching make this technique impractical. Therefore, other methods to discriminate against unwanted longitudinal modes have been devised [10, 11, 12, 13, 14, 15].

Presently, a frequently used method for obtaining axial mode control is that of utilizing a temperature tuned Fabry-Perot etalon inserted within the resonant cavity. This technique is highly effective, relatively simple, reasonably economical and, consequently, was chosen for use in this project. The etalon chosen consists of two sapphire optical flats seperated by a ceramic spacer and has a combined reflectance of 60 to 66%. The etalon was inserted in the resonant cavity such that it serves as the output mirror as well as longitudinal mode control device (Figure 10).

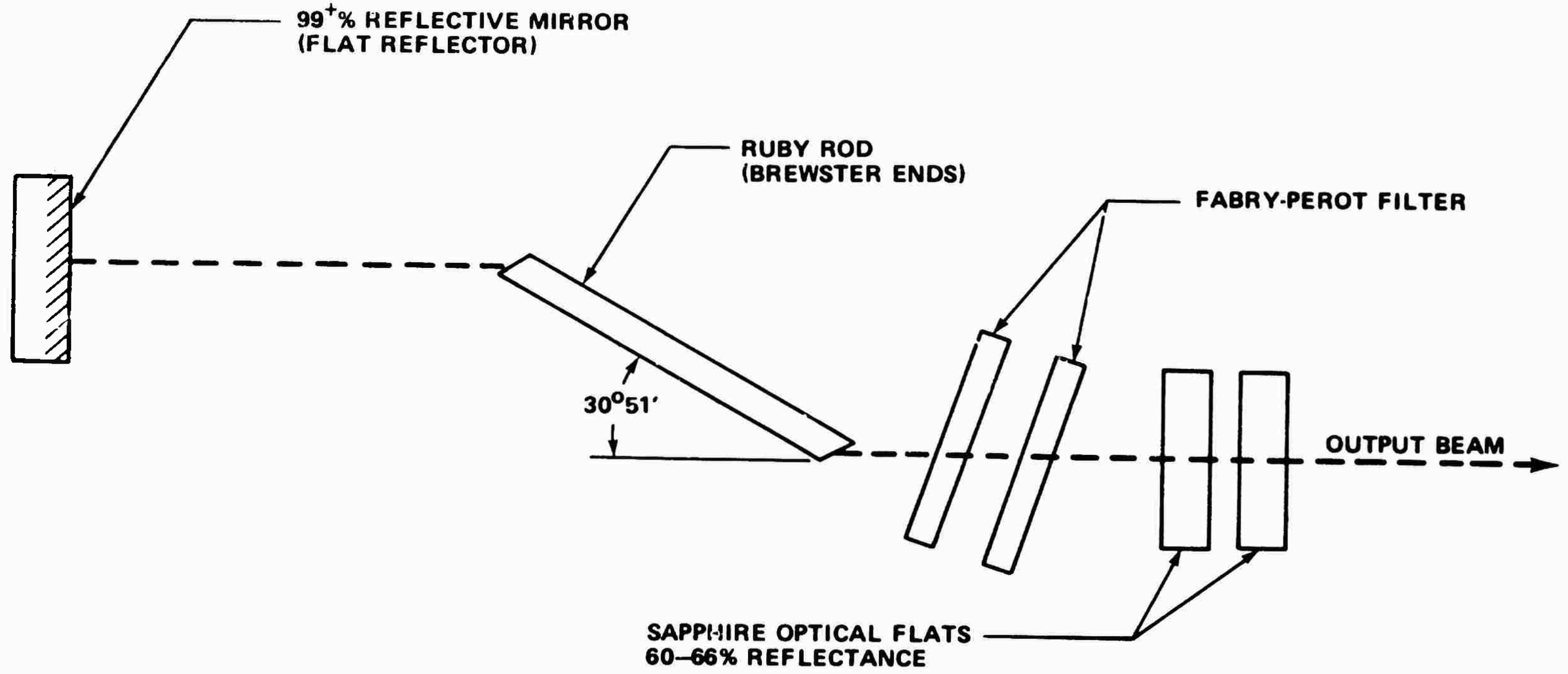


Figure 10. Resonant cavity with etalon output mirror and Fabry-Perot filter.

The etalon operates on the principle that the frequency bandwidth of the combined surfaces of the optical flats is much smaller than the bandwidth of the ruby. The light wave passes between the optical flats before being emitted and the number of possible axial modes is greatly reduced. A narrowing of bandwidth by nearly 99% when using this technique has been reported by Tiffany [12].

The distance between the sapphire optical flats has a significant effect on the bandwidth of the etalon and the distance must be held constant (within a small portion of one wavelength) if reliable and consistent mode control is to be maintained. This is done by controlling the temperature of the ceramic spacer which is separating the optical flats.

A more efficient selection of axial modes can be achieved by inserting a Fabry-Perot air spaced etalon in the laser resonator. The selection of a single axial mode can then be obtained by a slight tilt of the inner cavity etalon as shown schematically in Figure 10. The inner cavity etalon is the same as the pair used as an output mirror. Together with the ability to temperature control the etalons and the inner cavity adjustment, axial mode control was easily maintained. Alignment procedures and methods of temperature control will be discussed in this report.

c. <u>Laser Components</u>

(1) <u>Laser Head</u>. A high quality ruby rod is necessary for successful applications in holography. A Schlieren grade (Czochralski ruby rod with both ends cut at Brewster angles) was used in this system. The rod had the following properties: 0.05% C_r^{+++}, 1/4-in. diameter × 3 1/2-in. long, ends 1/10 λ flat and polished 2 to 4 arc sec parallelism, 60° orientation, 1/2 fringe/in. in a Twyman-Green Interferometer, and Brewster/Brewster ends (necessary for Q-switching without further need for polarizing prisms).

The laser head consists of a ruby rod and two flash lamps housed in a 3-in. section of cast aluminum. The cross section of the aluminum housing has the shape of a double ellipse with a highly polished inner surface (Figure 11). End plates for the housing were machined from 7075 aluminum and polished on metallurgical wheels using microcloth and 0.3 μ polishing alumina.

Spring clamps machined from beryllium copper are used as electrodes for the flash lamps. The lamps are held in position in the end plates by means of heat resistant, teflon end pieces that are bolted to the end plates. The ruby rod is held in position by two brass pieces with teflon inserts which hold the rod securely in position. Components of the laser head are shown in Figure 12 and the assembled unit is shown in Figure 13. The circular brass pieces may be rotated when positioned in the end plates. This allows for adjustment of the ruby rod.

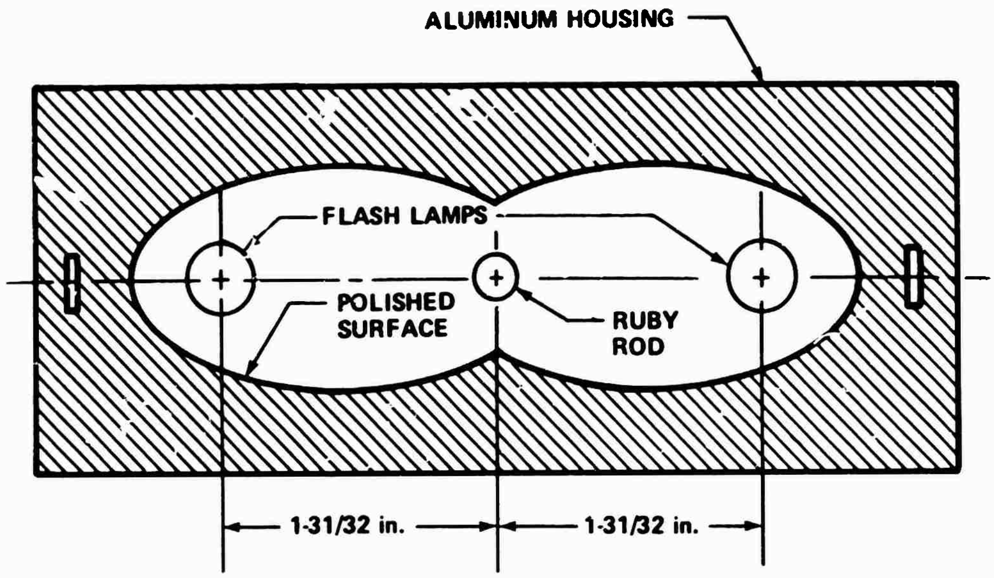


Figure 11. Cross section of laser head.

(2) Reflectors and Fabry-Perot Filter. The $99^{+}\%$ mirror is a flat dielectric reflector with a hard high field damage resistant coating. This coating can withstand power desities up to 500 MW/cm^2 in a 55-nsec pulse. This reflector is mounted in a Lansing mirror mount which provides for angular adjustment of the mirror.

The output reflector and Fabry-Perot filter were two Czochralski sapphire optical flats 0.50 in. in diameter by 0.125-in. thick with a 0° orientation separated by a 0.100-in. ceramic spacer. The optical flats are flat to within 1/20 λ and the spacer has a flatness to within 1/10 λ. The combined reflectance of each pair of etalons is 60 to 66%. Each etalon holder can be temperature controlled to within 0.09°F within a 5-hour period once thermal equilibrium has been reached. A 3-minute period is required to reach thermal equilibrium at each temperature setting. Figure 14 shows the etalon holder with the temperature control. Temperature is maintained electronically (the electronics will be described later). The entire etalon assembly is mounted in a Lansing mount for easy angular adjustment.

(3) Pockels Cell and Pulse Recording. Control of the laser output is achieved by using a Pockels cell. The cell is placed in the resonator cavity between the laser head and the $99^{+}\%$ mirror (see Figure 15). The cell is oriented so that the applied electric field is rotated 45° from the direction of polarization of the light emitted from the Brewster-cut ends of the ruby rod. When the flash lamps are fired, a quarter wave voltage (i.e., the necessary voltage to cause temporary quarter wave retardation) is applied to the Pockels cell. The plane polarized light from the ruby rod passes through the cell and is retarded by

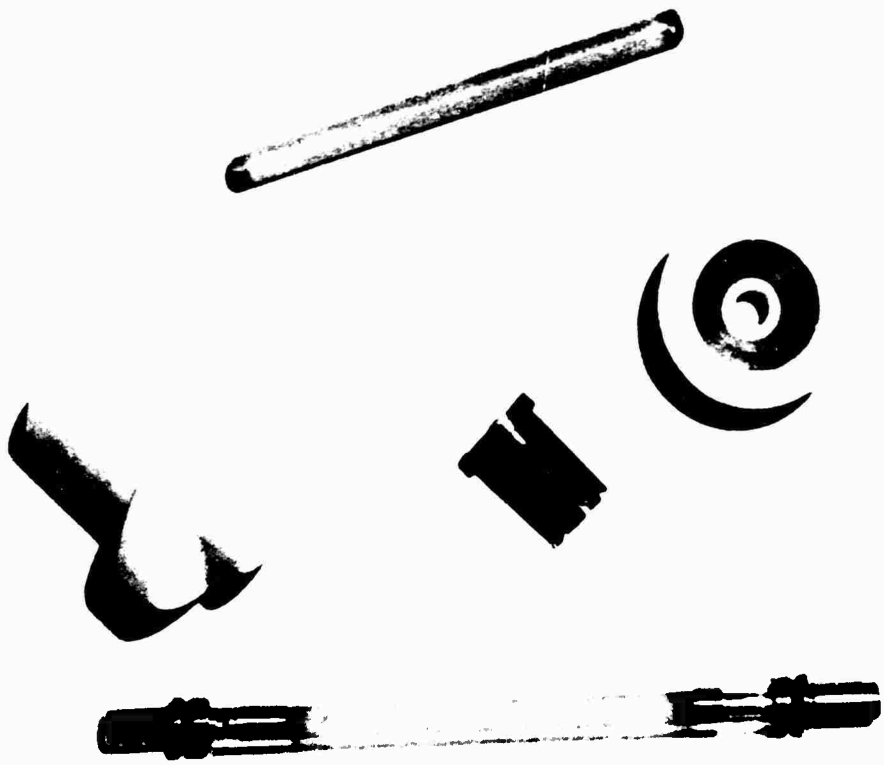


Figure 12. Components of ruby laser head

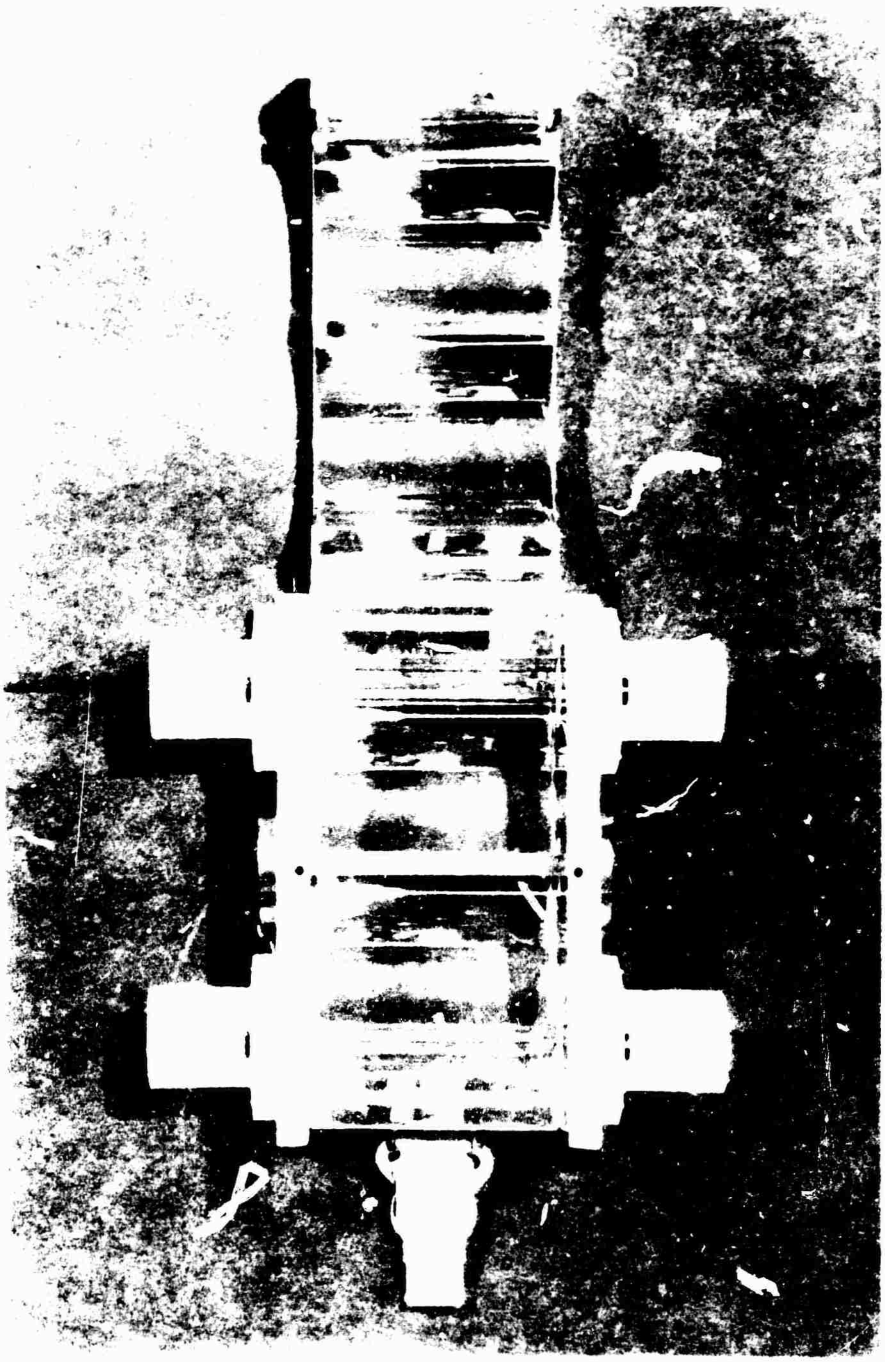


Figure 13. Assembled ruby laser head.

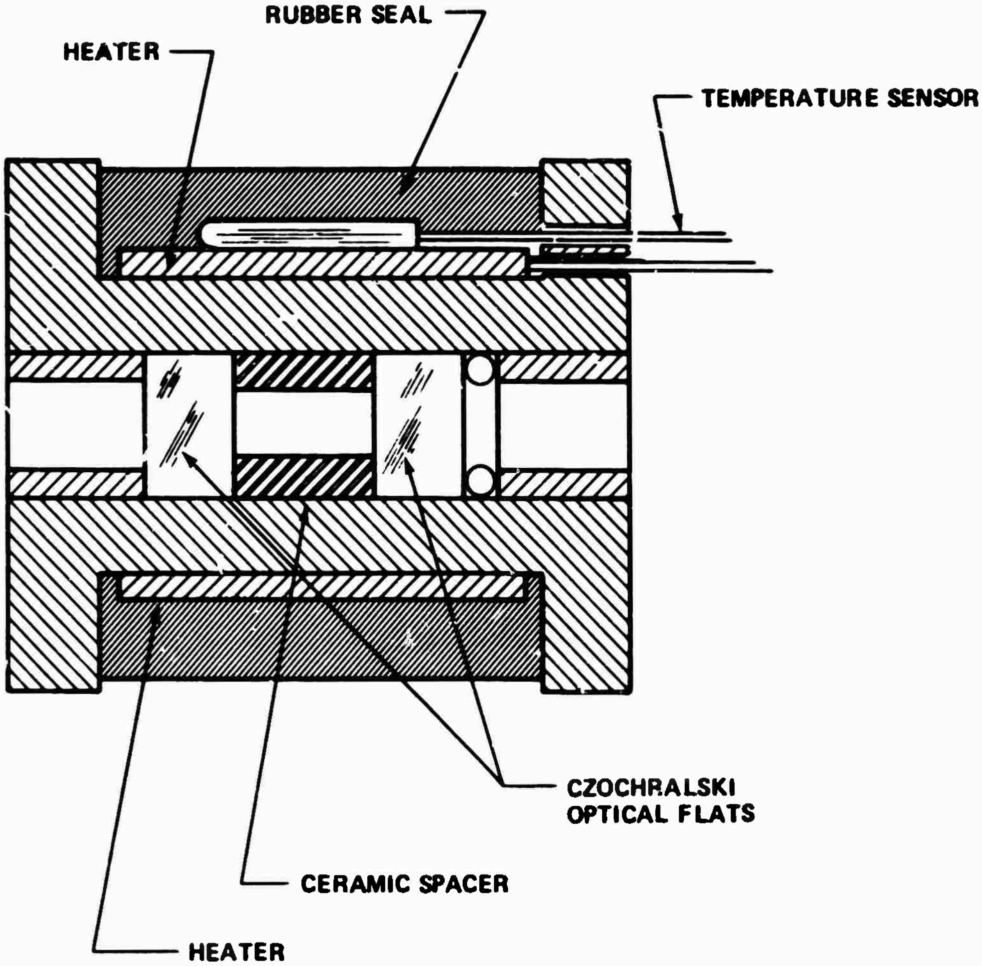


Figure 14. Etalon holder with temperature control.

one quarter wave. After reflecting off of the $99^{+}\%$ mirror, the light passes back through the Pockels cell and is further retarded so that a net retardation of one-half wave has now occurred. The direction of polarization, then, has been rotated 90° and is now parallel to the face of the ruby rod. This causes complete reflection of the light at the face of the rod so that none of the light energy travels back through the ruby material. In practice, a small amount of light is fed back through the ruby rod due to reflections at the face of the Pockels cell, but it is an insufficient amount to cause lasing to occur. The voltage is maintained on the Pockels cell long enough (typically 500 μsec) to allow the ruby rod to reach a highly excited state and then is quickly turned off. The Pockels cell then becomes optically isotropic and allows the emitted light to pass through unaffected. Photons then traverse back through the highly excited rod producing a giant pulse. The resulting pulse shape and pulse timing are reproducible. Pulse widths are typically 40 to 50 nsec.

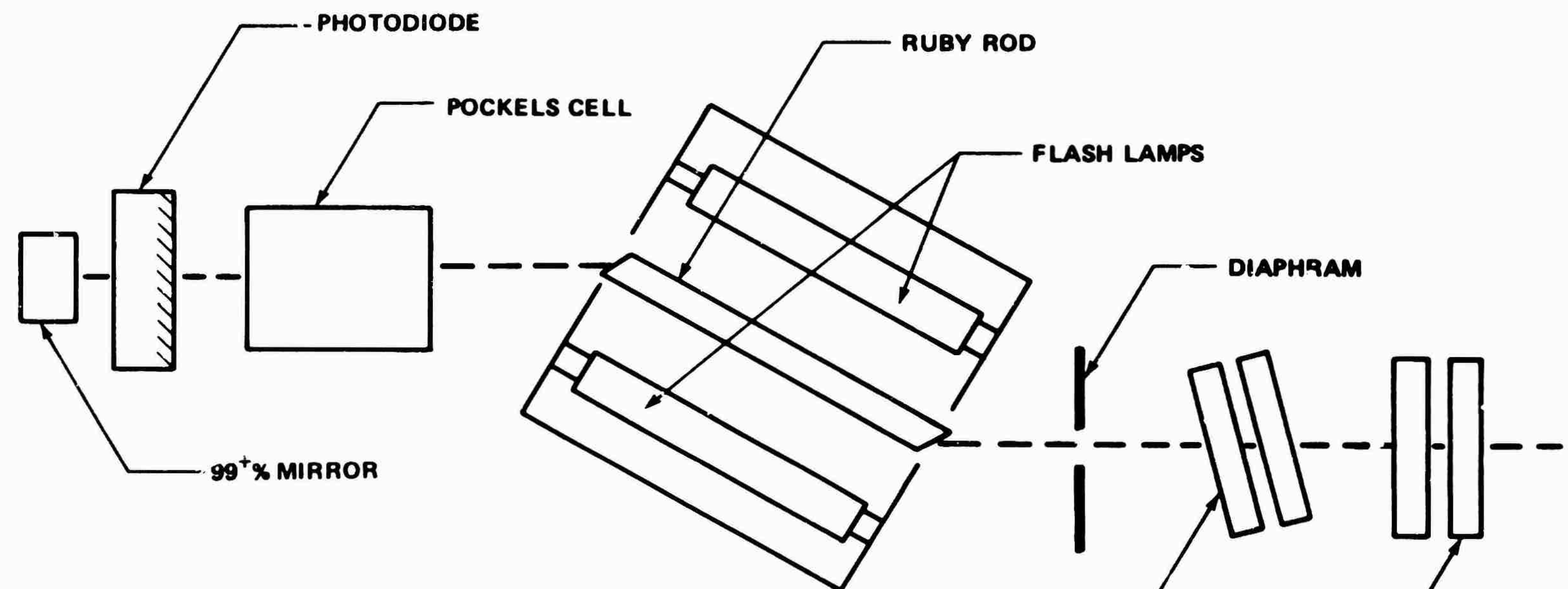


Figure 15. Resonant cavity for a single mode pulse output

The ruby output may be recorded by means of a photodiode placed behind the $99^{+}\%$ mirror. The necessary equipment for monitoring, timing, and powering the flash lamps and Pockels cell is described in succeeding paragraphs of this report.

The laser system with all components mounted on an optical bench is shown in Figure 16. The system has been proven to be adequate for a high speed light source.

Output power of this laser system was measured for a single Q-switched pulse, and only delay times were changed. The results are shown in Table 1.

TABLE 1. OUTPUT POWER FOR RUBY LASER MEASURED FOR A SINGLE Q-SWITCHED PULSE

Delay (msec)	Output (mJ/pulse)
0.92	17.8
1.00	29.5
1.20	67.0
1.60	74.0
2.00	4.0

A test was also conducted with a random lase, the results being 254 mJ/1000 pulses or 0.254 mJ/pulse.

d. Electronics

(1) Laser Power Supply. A schematic diagram of the laser power supply is shown in Figure 17. When the flash lamps are located close to the surface of the laser cavity (as they do in this case), they may be triggered by applying a high voltage pulse to the laser head. This power supply allows for a 35-V pulse to be applied to the laser head to trigger lamps are connected in series and the power supply can apply a maximum of 3 V to discharge the flash lamps. When now, the lamps require a maximum discharge voltage of 2V. However, after several firings, the flash lamps would discharge reliably at 1.4 V. The energy input of 590 J at 1.4 V was below the threshold of lasing. Lasing would generally occur at a energy input of 675 to 770 J. For single mode operation in holography, the laser should be operated just above the threshold level. At this discharge voltage, the flash lamps are not highly taxed and should be good for many thousands of firings.

(2) Pockels Cell Power Supply. The Pockels cell driver and modulator are an integral unit and the circuit diagram is shown in Figure 18. The driver is triggered by a 100-V pulse supplied by a Hewlett Packard Pulse Generator, model 214-A. A quarter wave bias voltage of 6.2 V is applied across the Pockels cell to prevent lasing. The voltage is reduced to zero by the 100-V pulses from the pulse generator

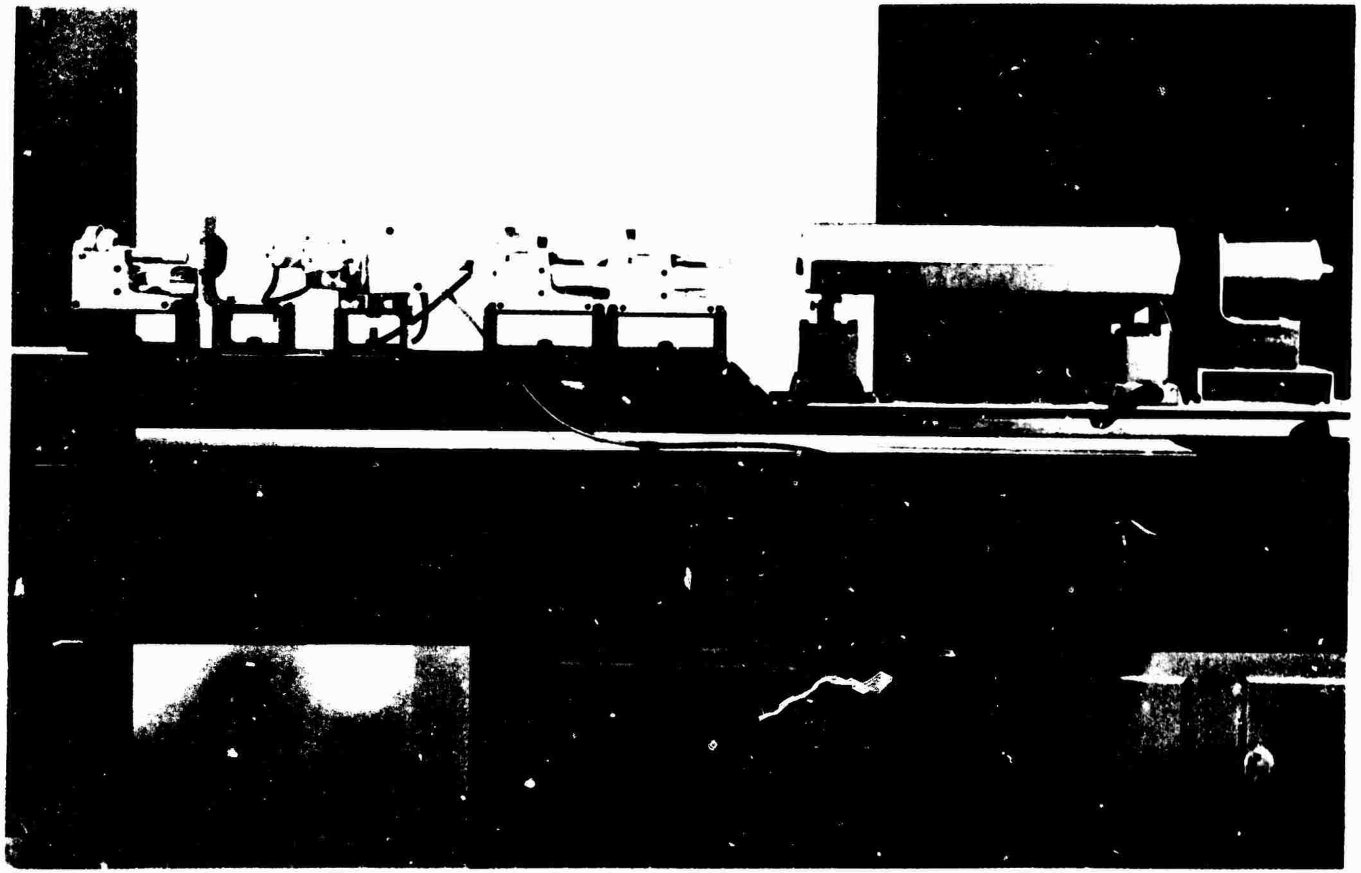


Figure 16. Photograph of ruby laser system.

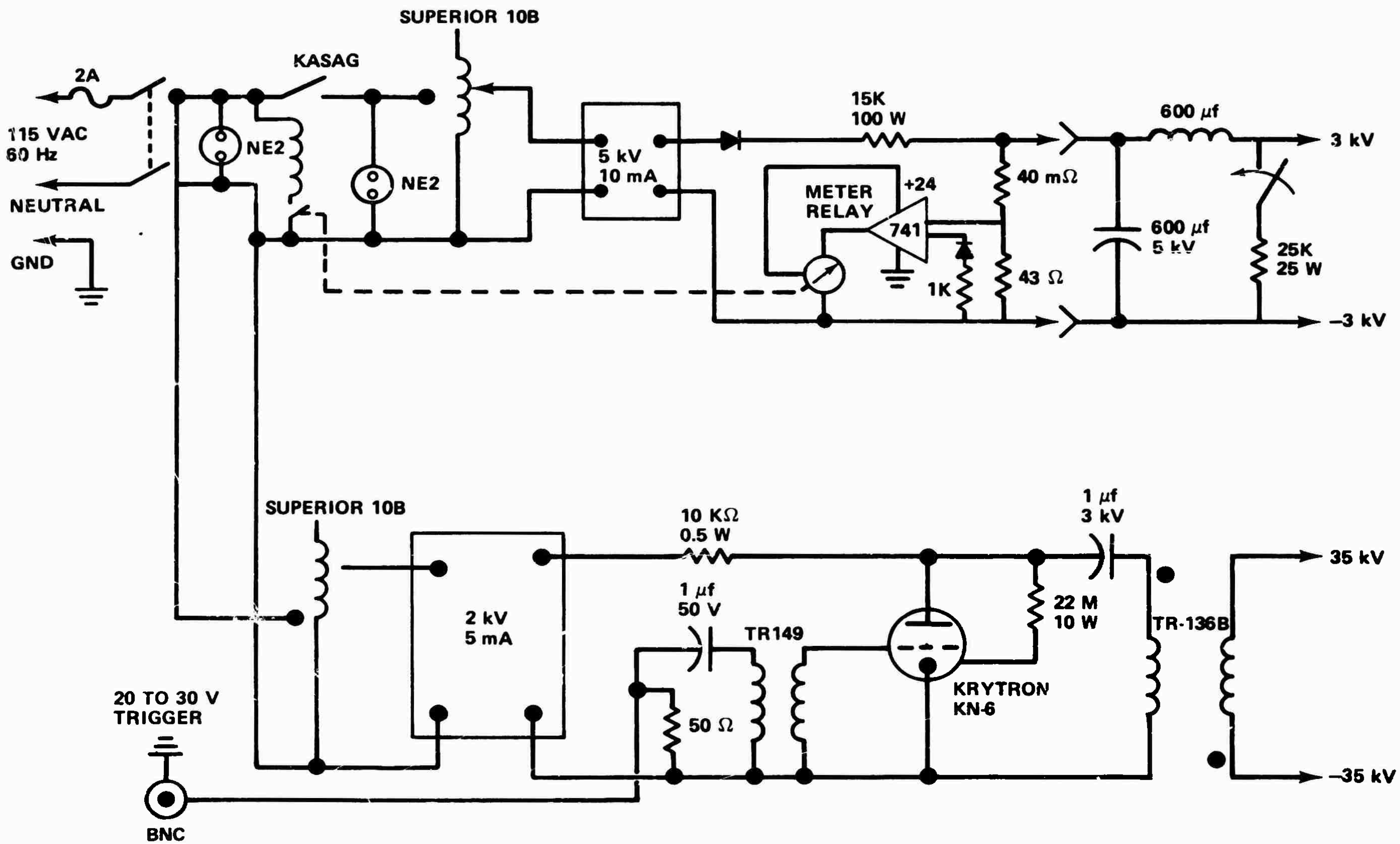


Figure 17. Laser power supply.

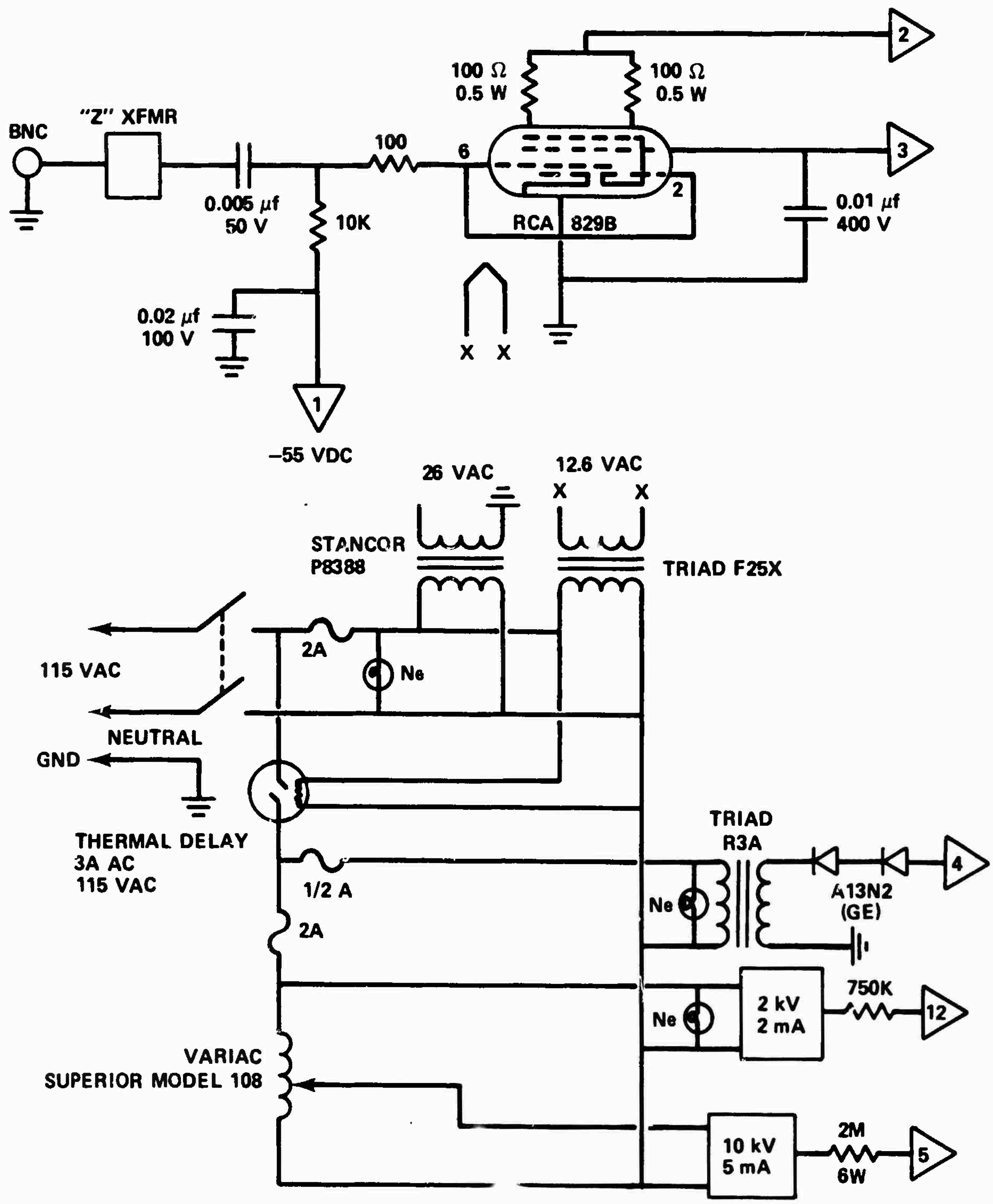


Figure 18. Pockels cell power supply and switching unit.

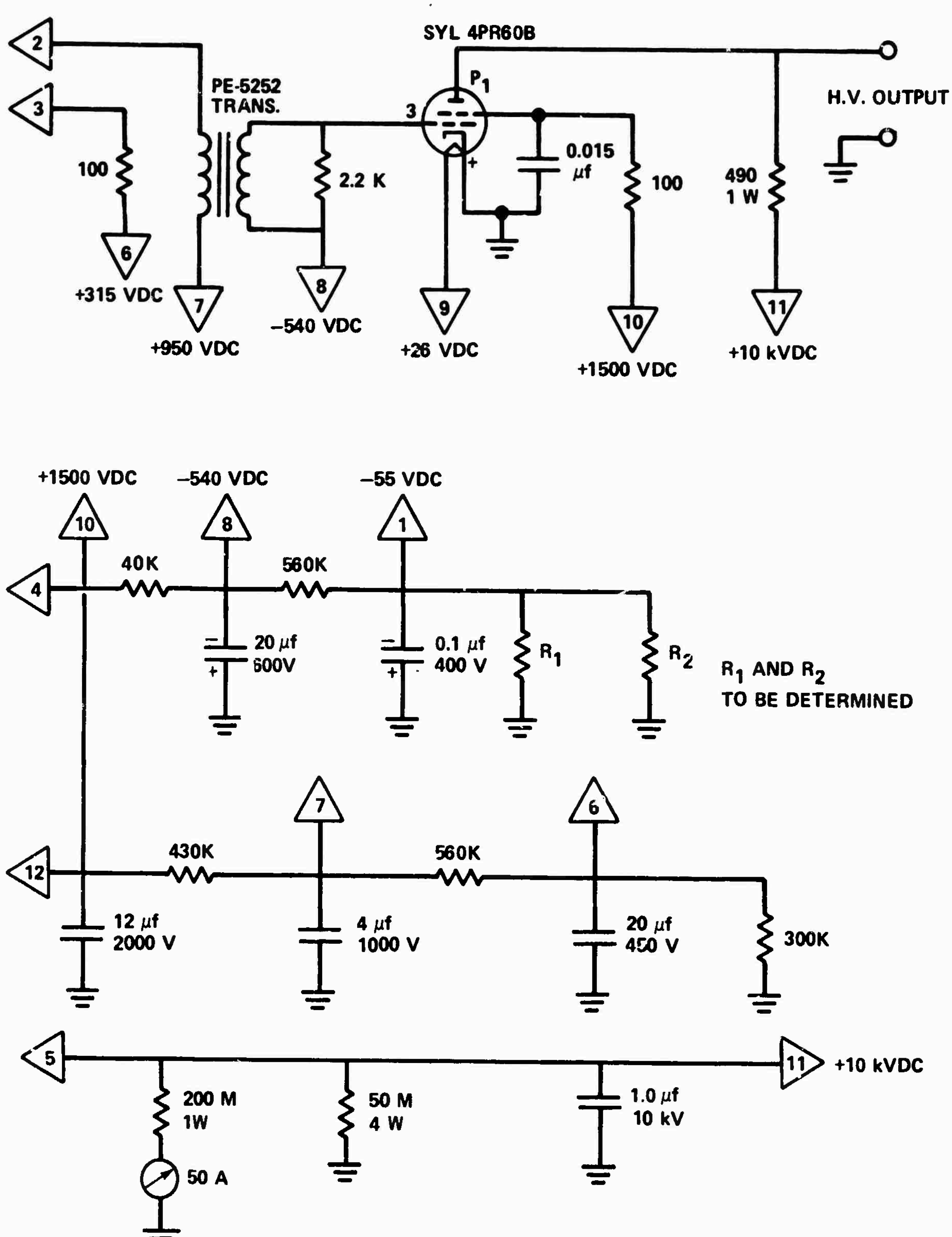


Figure 18. (Concluded)

at which time a Q-switched laser pulse is emitted. The voltage is reduced to zero in 25 nsec, and the light output duration is typically 50 nsec. Other types of modulation can be used [6]; however, for multiple Q-switching, the Pockels cell is very reliable.

(3) Etalon Heater Control. Single mode operation of the ruby laser is achieved by several methods each of which is used in this system. Controlled temperature of the etalons is one technique. The temperature is maintained and monitored electronically by a heating device with the circuit diagram shown in Figure 19.

The heater consists of 30 parallel heating elements (1/4-W resistors) spaced equally around the etalon holder (Figure 14). It delivers 2.8 W at 24 V and is sufficient to maintain the etalon at any temperature up to 130°F at a 68°F temperature.

Temperature readout is provided by a Yellow Springs Instrument Company Thermilinear Thermistor Network (part No. 44204). This device produces a voltage output which is highly linear with temperature.

Feedback for the temperature control circuit is provided by a Fenwal GA51J1. Both of these thermistors are mounted in the etalon holder. Figure 20 is a graph of the etalon temperature for several settings over a 5-hour period. This stable temperature is sufficient for good longitudinal mode control of the laser.

(4) Photodiode Circuit. The photodiode circuit used for recording the laser output is shown in Figure 21. The photodiode has a response time of less than 10 nsec. The photodiode used in this circuit is an EGG SGD 100A.

e. Controlled Output of the Laser

(1) Single and Double Pulse Operation. A Q-spoiled laser pulse occurring at preselected times is necessary to record high speed events in dynamic photomechanics. The equipment used to modulate the laser is shown in Figures 22 and 23. The oscilloscope is a Textronix Model 549 with two time bases, one delayable with respect to the other.

The Hewlett Packard pulse generator is capable of generating either a single pulse or a double pulse when triggered from the delayed trigger out of the oscilloscope. The pulse generator then provided the trigger to the high voltage power supply for the Pockels cell.

Referring to Figure 22, the order of events to achieve a single Q-switched pulse were as follows. The oscilloscope was used in time base B intensified by time base A. With this setting, the time base A was delayable with respect to B. Gate B was used to trigger the flash lamps and gate A was used as an external trigger for the pulse generator. The delay between the trigger to the flash lamps and the Q-switch trigger was 1.0 to 1.2 msec as shown in Figure 1. A double pulse output was easily

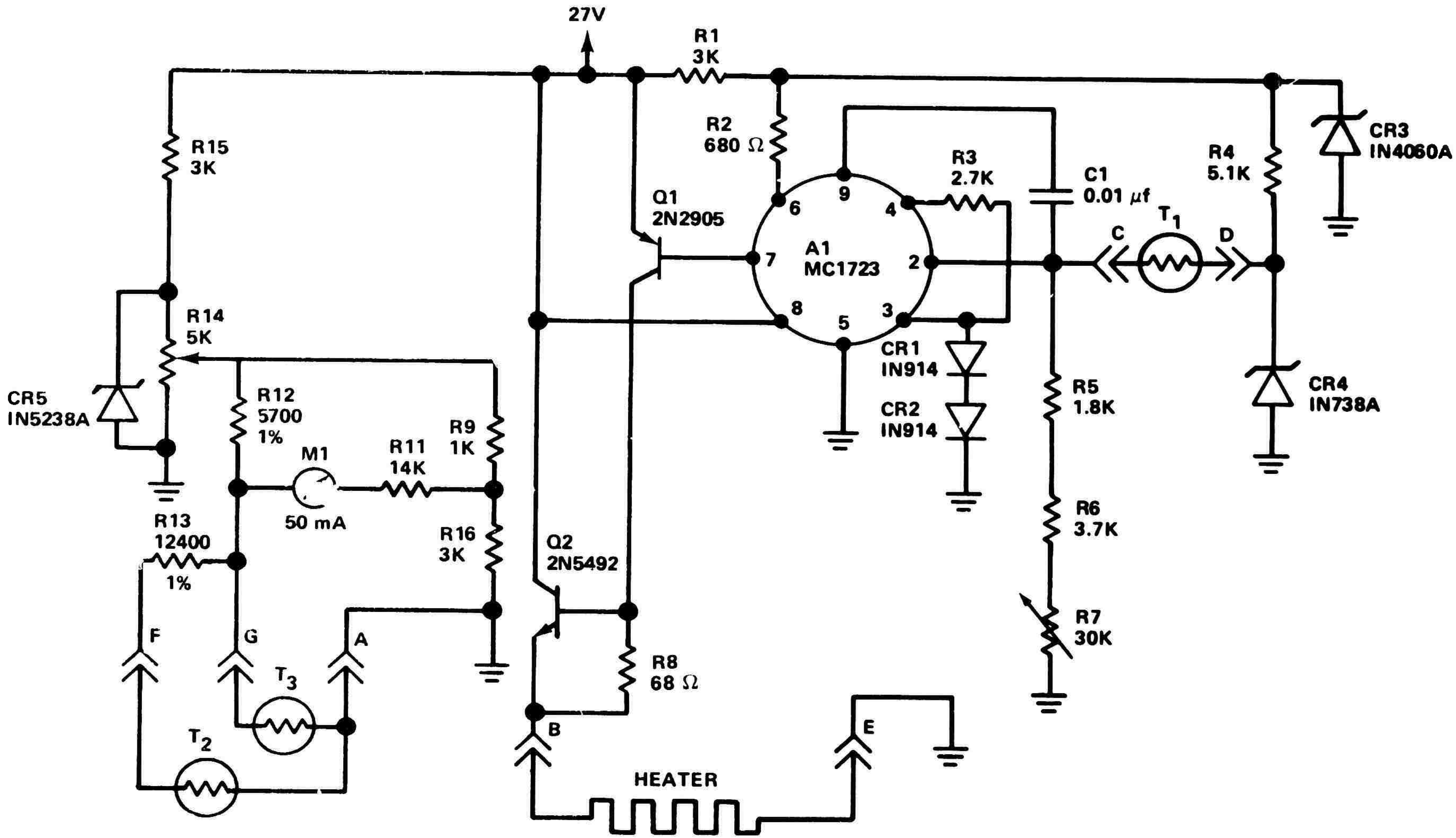


Figure 19. Schematic diagram for eatlon heater control.

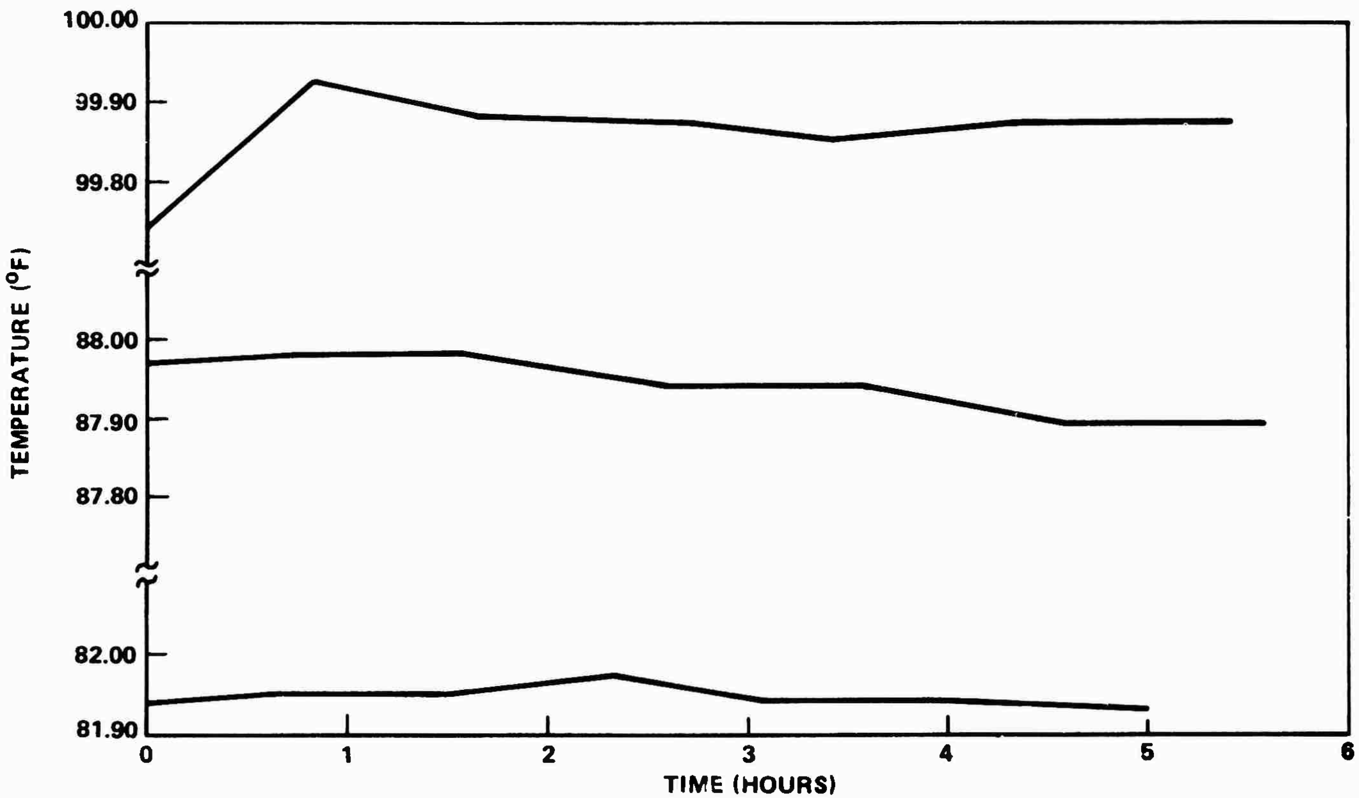


Figure 20. Temperature chart for eatlon heater.

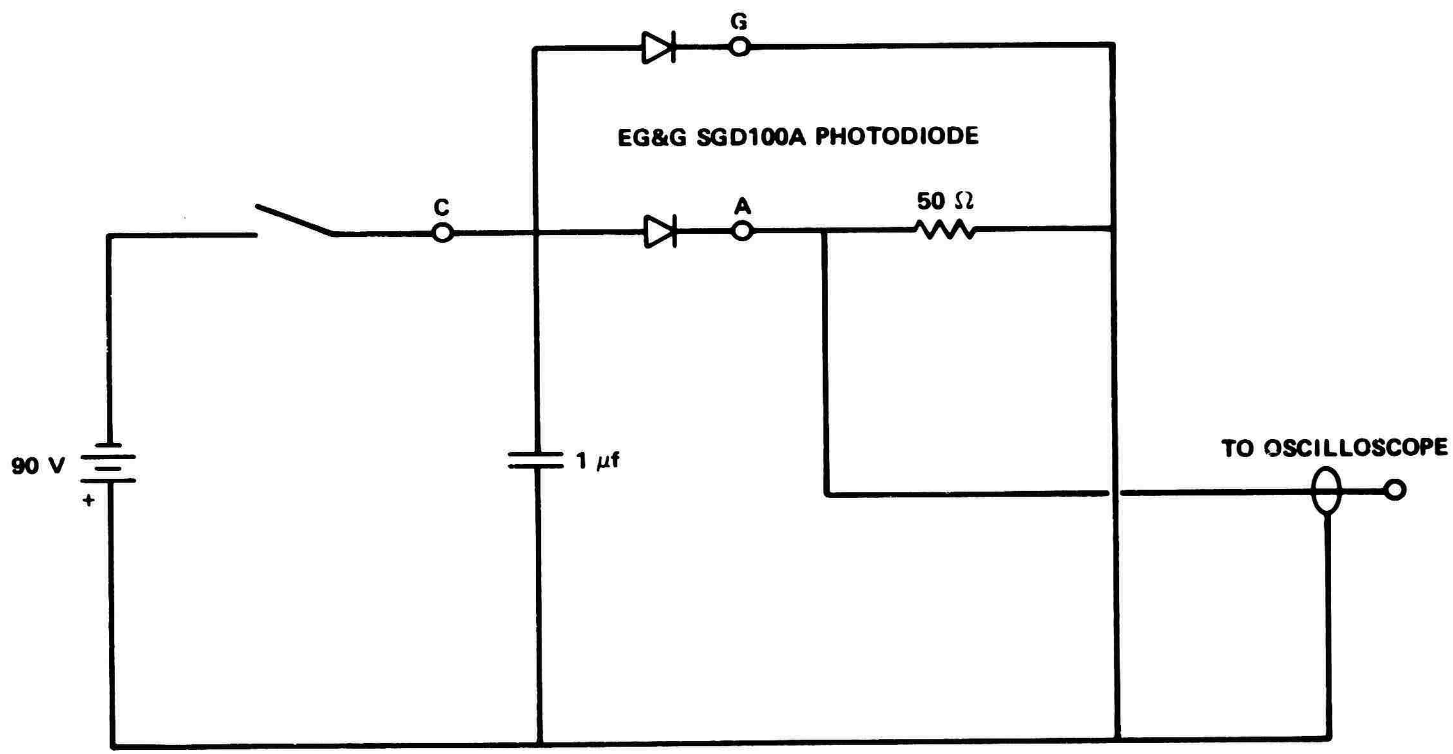


Figure 21. Photodiode circuit.

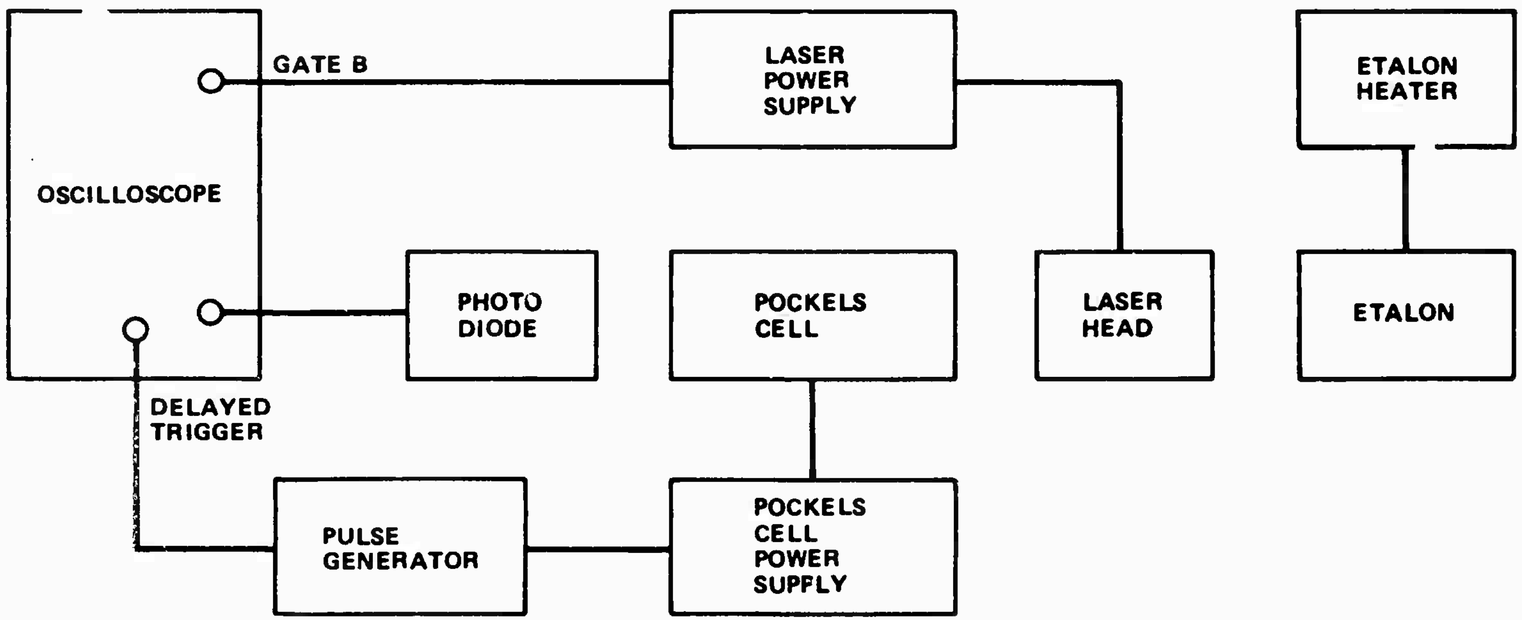


Figure 22. Diagram of modulated ruby laser system for single and double pulse operation.

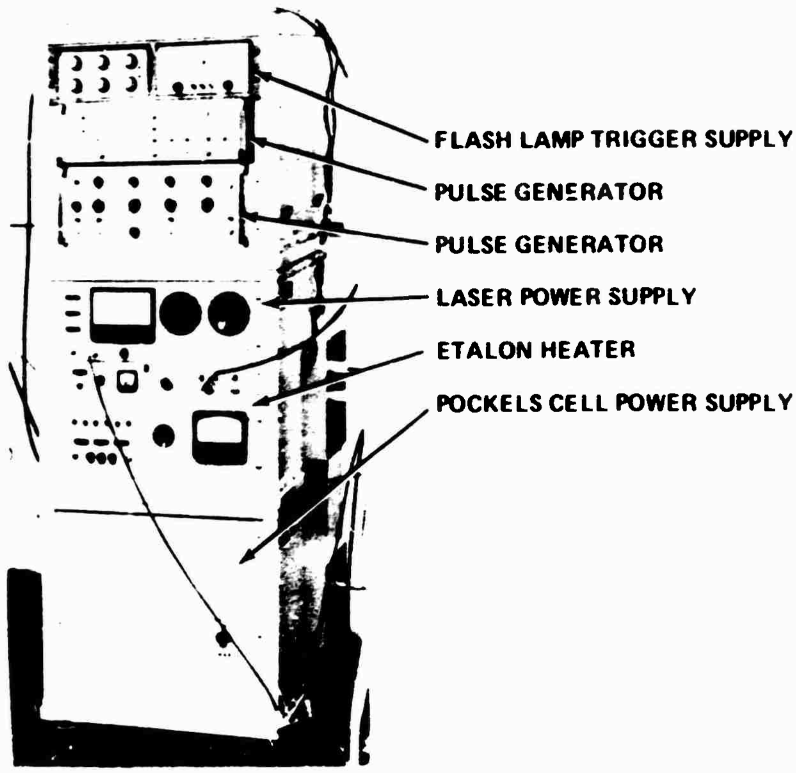


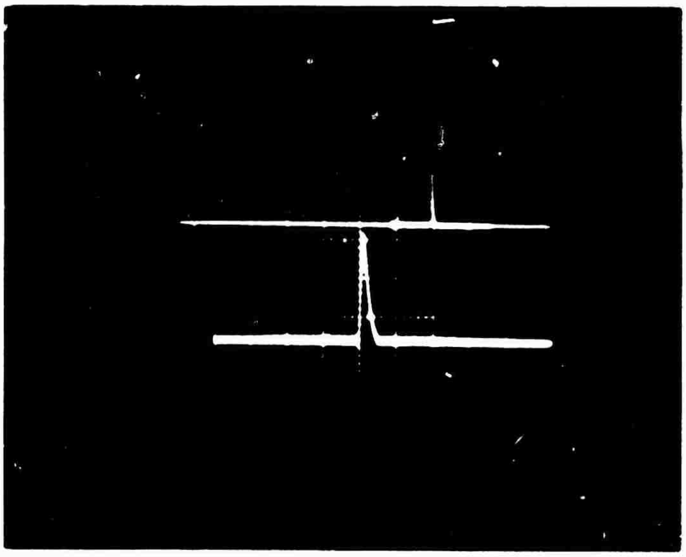
Figure 23. Control panel for modulated ruby laser system.

obtained from the single pulse setting. The Hewlett Packard model 214-A pulse generator has a double pulse feature. The second pulse can be delayed with respect to the first internally in the pulse generator. Figure 24 shows an oscilloscope record of a single and double pulse output from the ruby laser.

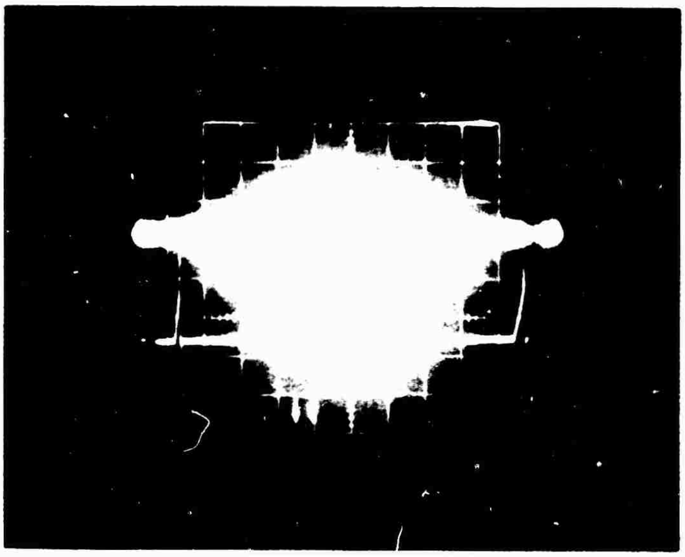
(2) Multiple Pulse Operation. For multiple pulse operation, refer to Figure 25. The operation is the same as the single and double pulse with the addition of another pulse generator. The additional pulse generator can be synchronous gated to provide a pulse train as long as the applied gate is operating. This pulse generator then acts as an external trigger for the Hewlett Packard model 214-A pulse generator which operates the Pockels cell power supply. Figure 26 is an oscilloscope record of multiple Q-switched pulse output from a ruby laser.

f. Alignment

The alignment of the ruby laser is relatively simple. As illustrated in Figure 27, an He-Ne laser is placed at the end of an optical bench. The beam is made to pass through the two separated iris diaphrams which is the alignment beam for the ruby rod. The ruby rod is then



(a) Single Q-switched pulse.



(b) Double Q-switched pulse.

Figure 24. Single and double Q-switched output from ruby laser.

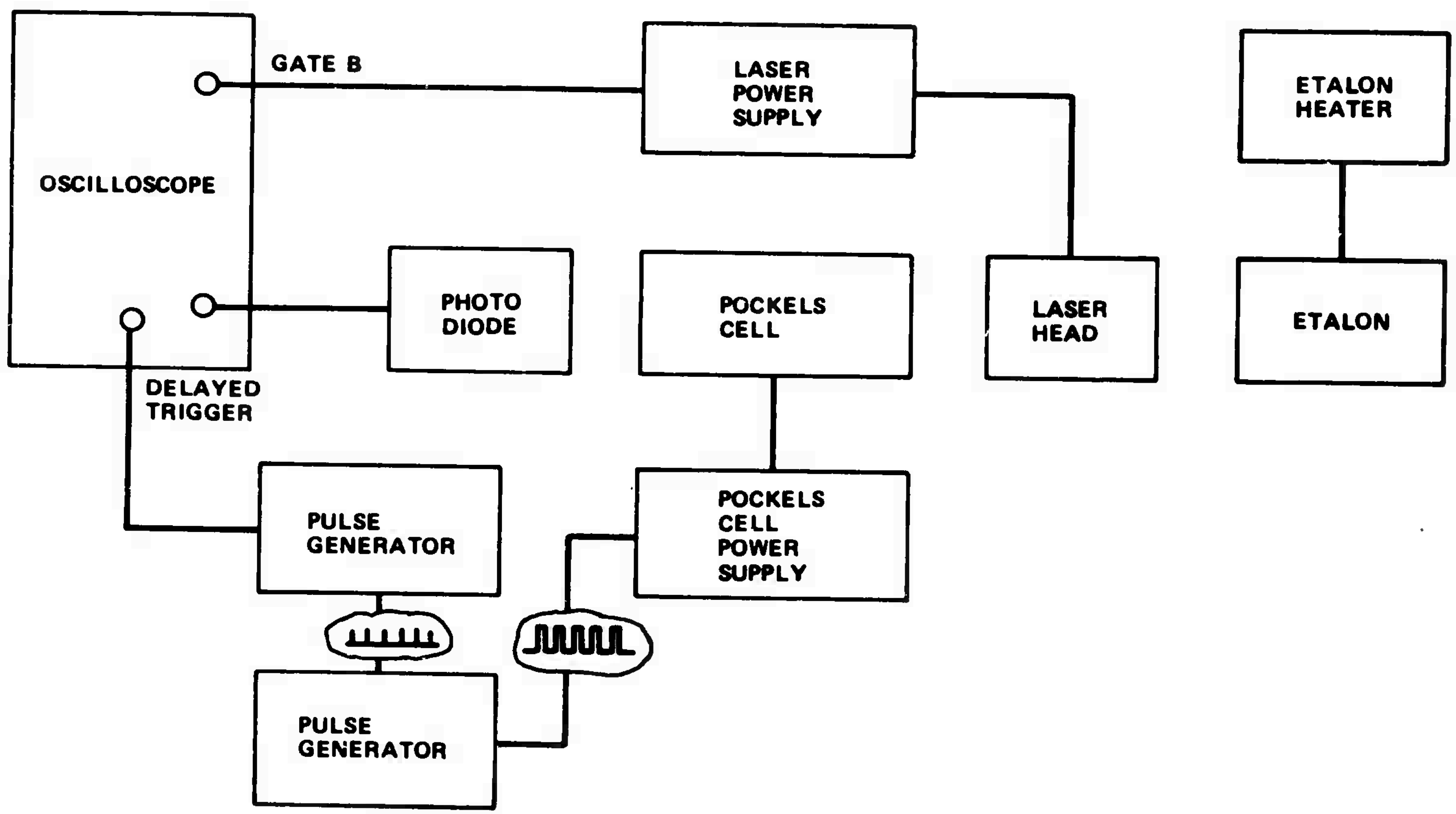


Figure 25. Diagram of modulated ruby laser system for multiple pulse operation.

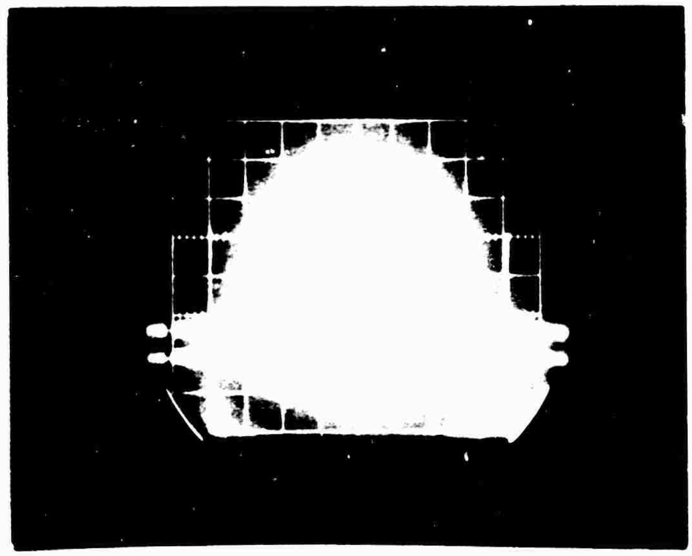


Figure 26. Multiple Q-switched output from ruby laser.

oriented at the Brewster angle and centered in the light beam. Lateral adjustment of the laser head mount is then made to ensure that the light beam enters and emerges from the center of the faces of each end of the rod. Care should be taken to insure that the rod is in the correct position, otherwise the laser will not operate efficiently. Next the $99^{+}\%$ mirror and Pockels cell are aligned. These elements are adjusted until the reflected spot from the mirror and front surface of the Pockels cell are coincident with the alignment beam. This is accomplished by centering the reflected spot on the center of the iris diaphrams — then the mode control diaphrams. Next the mode control diaphram and Fabry-Perot filter is aligned. The mode control diaphram is the beam. The Fabry-Perot filter is adjusted until the reflected spot off the front surface is coincident with the alignment beam. At this time in the alignment procedure, the output mirror is not even in the system. If the laser is to be used for photoelasticity or Moire' analysis, then the Fabry-Perot filter can be used as the output mirror and no further adjustments are necessary. The laser can then be used without inserting the additional etalon in the system. However, for holographic interferometry applications, the output etalon is to be inserted in the system. With the output etalon out of the system, the laser is fired for random lasing and the Fabry-Perot filter is slightly tilted until lasing does not occur. If lasing no longer occurs when the flash lamps are fired, then the Fabry-Perot filter is in the correct position. Then the output etalon is placed in the system and adjusted so that the reflected spot from the front face of the etalon is coincident with the alignment beam. The ruby laser is now in the correct alignment for use in holographic interferometry applications.

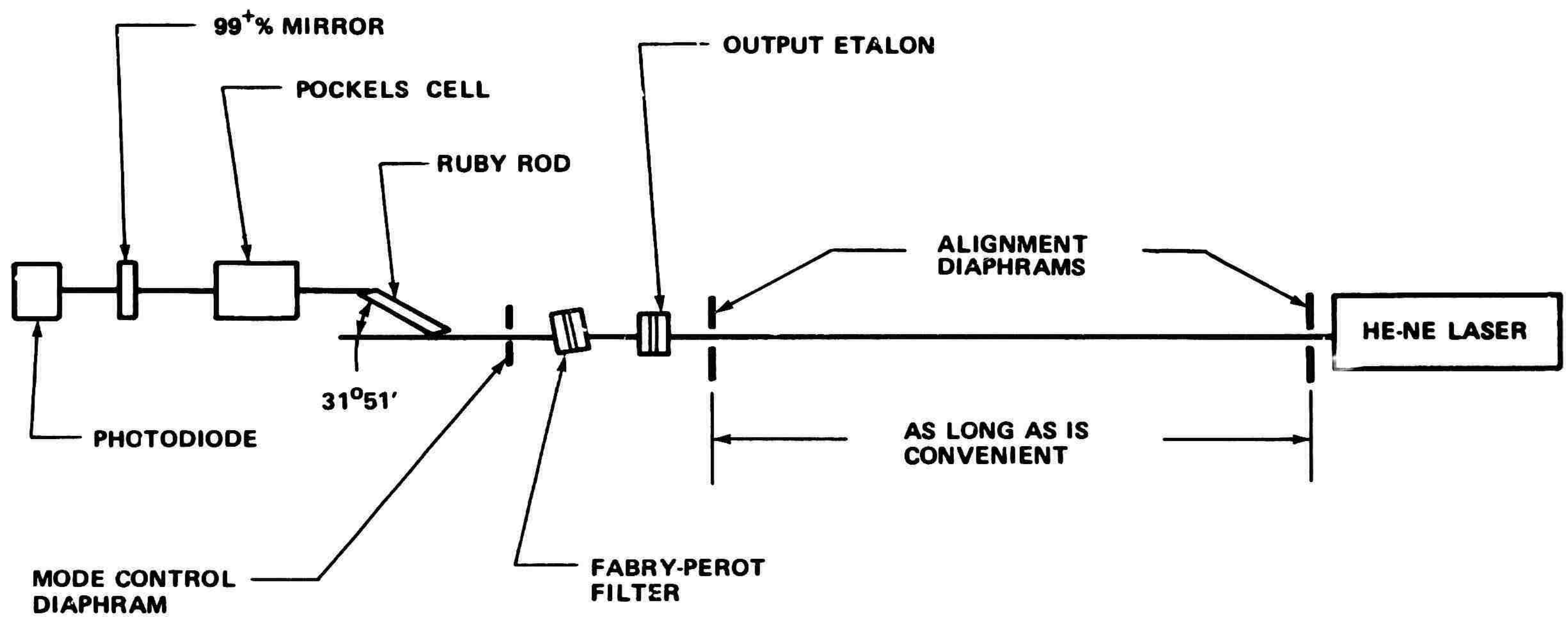


Figure 27. Arrangement for ruby laser alignment.

3. Application of the Ruby Laser to Dynamic Photomechanics

a. Introduction

The area of dynamic photomechanics has received considerable emphasis in recent years. Pulsed ruby lasers have been used extensively in the application of photoelasticity to wave propagation problems. Rowlands [6] gives a thorough list of dynamic photoelastic work done before 1967. More recently however, holography has been demonstrated to be a tool of promising potential for application in dynamic photomechanics. The use of holographic interferometry and holographic photoelasticity for studying dynamic problems has been demonstrated by Ranson [4] and Holloway [3,5]. Other important studies illustrating the applicability of holography to dynamic photomechanics have been made by other investigators [16, 17, 18, 19, 20].

The ruby laser system described herein was designed specifically for use in dynamic photomechanics. Since photoelasticity studies have been reported extensively, applications to photoelasticity will not be discussed. The interested reader is referred to the literature for this subject. Applications for holography and a multiple Q-switching experiment using shadow Morie´ analysis will be discussed. Also the theory of each technique will not be presented in this report. For a discussion of the theory of the principles of holography, refer to References 21, 22, 23, 24, 25, 26 and 27.

b. Holographic Interferometry

An example chosen to illustrate the double exposure technique of holographic interferometry is the central impact of a flat plate. The geometrical configuration for this example is shown in Figure 28. The material used in this example is a unidirectional fiber glass composite plate 0.040-in. thick. The fiber direction was horizontal and the load was a small explosive charge. Figure 29 is a photograph of the virtual image of the composite plate 30 μsec after impact.

Film used to record the holograph was AGFA 10E75. This film has a peak sensitivity at 6943 Å and a resolving power of 2800 lines/mm.

c. Multiple Q-Switched Ruby Laser Applied to Shadow Moire´ Analysis

An example chosen to illustrate the multiple Q-switching technique of the ruby laser is the central impact of a steel plate using shadow Moire´ and a high speed camera. The geometrical configuration of this experiment is shown in Figure 30. The laser was multiple Q-switched at the maximum speed of a 16-mm streak camera. The maximum framing rate was 10,000 frames/sec. The laser is capable of framing rates greater than 100,000 frames/sec, therefore the camera speed limited the operation of the laser. Figure 31 is a photograph of three 16-mm frames of the plate during impact. Figure 32 is an enlarged photograph of the middle frame.

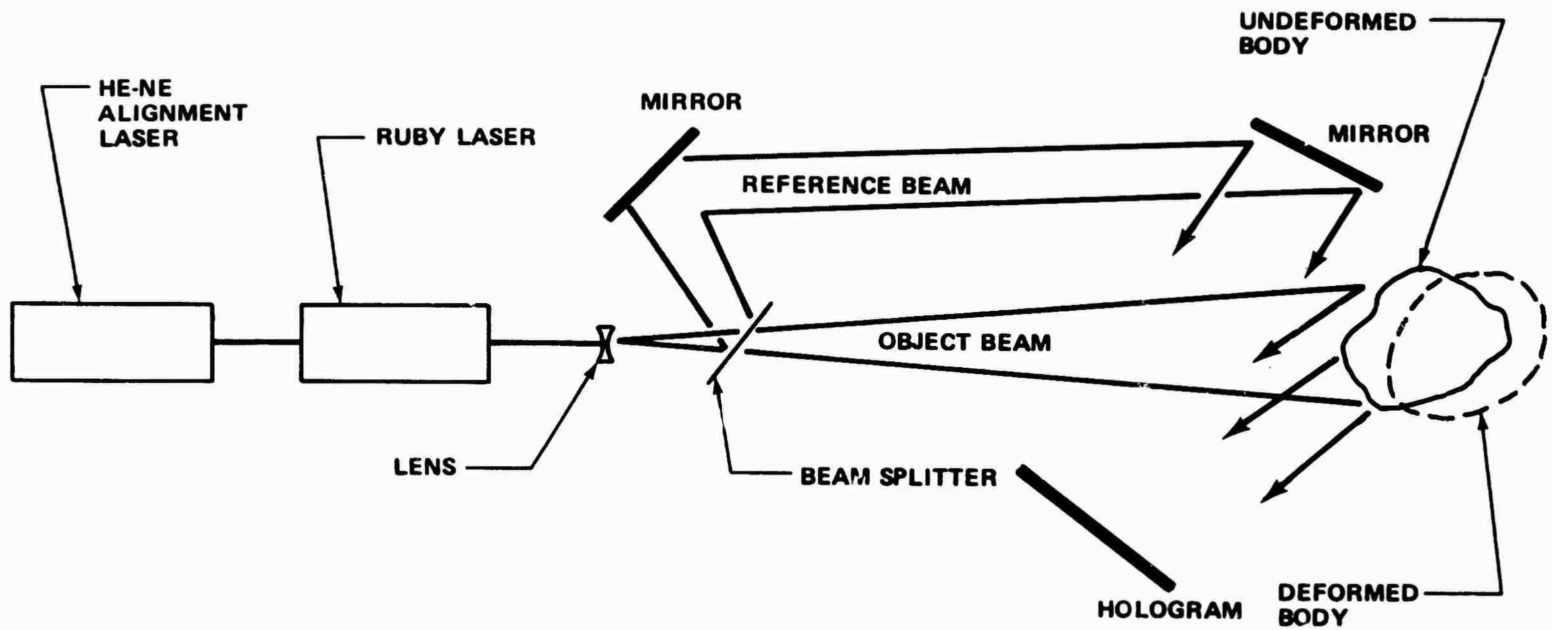


Figure 28. Schematic of a double exposure dynamic holographic arrangement.

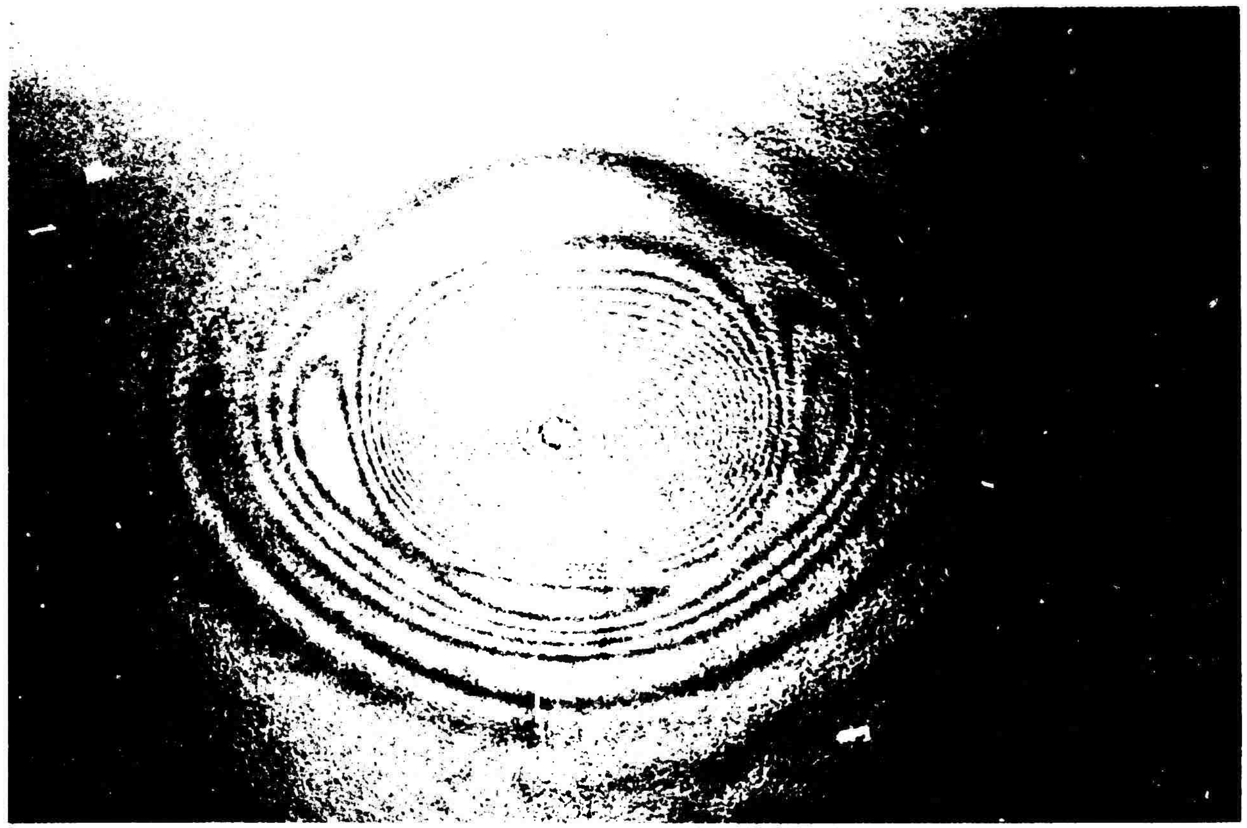


Figure 29. Photograph of a unidriectional composite plate 30 nsec after impact.

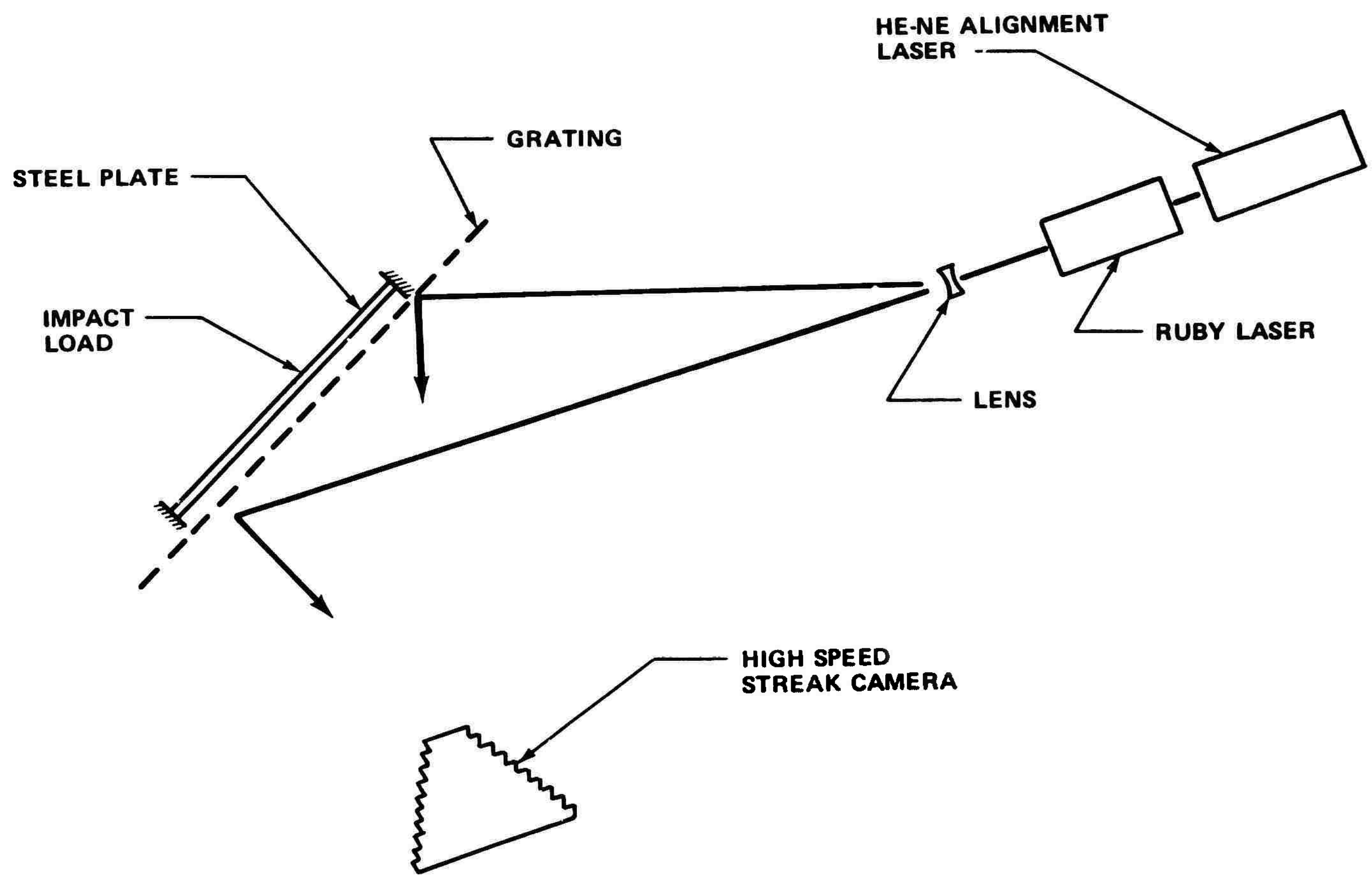


Figure 30. Multiple Q-switched laser applied to shadow Moire' analysis.

The film used to record the event was Kodak Linagraph Shellburst film which has an extended red sensitivity.

Figure 31. Shadow Moire' photographs of central impact of a framing rate is 10,000 ft/sec.

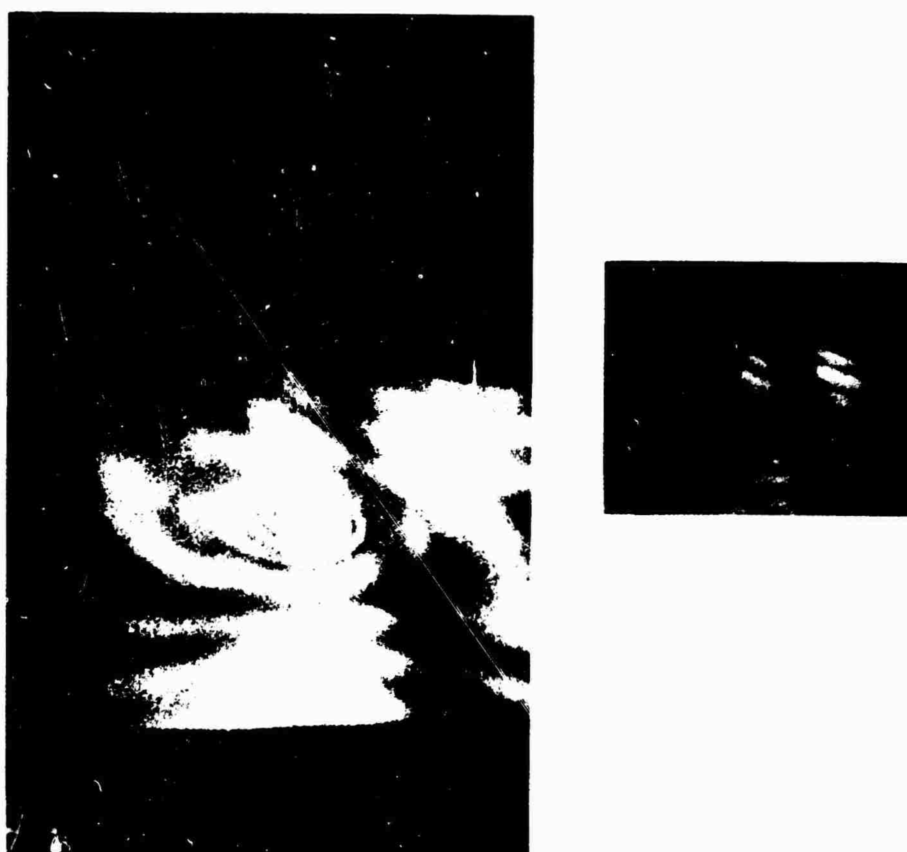


Figure 32. Enlarged photograph of the center frame of Figure 31.

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